FERMILAB-Proposal-0629

Proposal to Fermilab to Measure Direct Photon Production in Hadron-Nucleus Collisions

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14 pgs

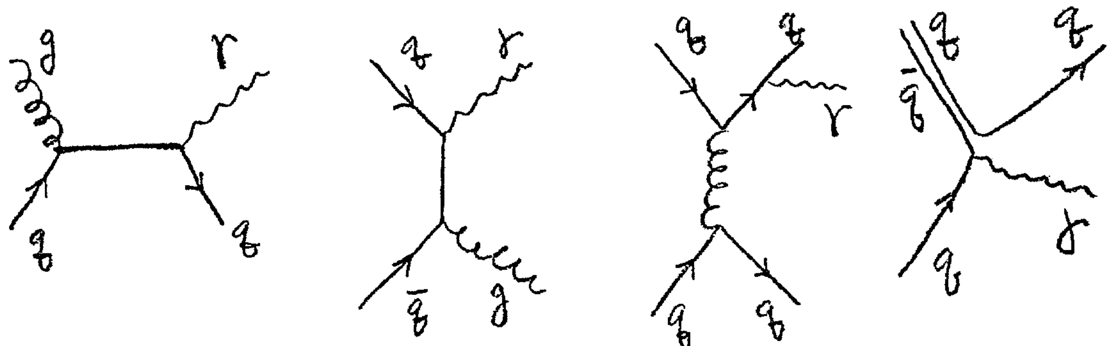
Abstract

We propose to measure the yield of direct photons produced at large transverse momentum (p_T) in π^+-nucleus and p-nucleus collisions at 200 GeV/c. At the same time we intend to examine the properties of hadronic jets produced in association with these photons. These questions have important bearing on the QCD theory of the strong interactions. Our specific goals are to determine the γ/π^o ratio as a function of p_T in meson-nucleus reactions and to confirm previous results for proton-nucleus collisions. Information that we will obtain on the γ/π ratio and on the nature of the accompanying hadrons will also be used to optimize the design of a more comprehensive Tevatron experiment.

The proposed experiment is to be performed with the equipment that was used in the recently completed experiment E272, supplemented by the hadron calorimeter of E236. The trigger will require the deposition of electromagnetic energy at large p_T in our fine-grained liquid-argon calorimeter. This proven photon detector will remain in the present position for this experiment, while some of the track chambers will be rearranged to straddle both sides of the M-1 beam line. The hadron calorimeter will be placed on the side opposite to the photon detector. To minimize overall down-time we plan to execute our experiment in the West branch of the M-1 beam. We are requesting 200 hours of time to debug our equipment and 400 hours of time for data taking. A positive beam with $\geq 3 \times 10^7$ particles/spill is required for this experiment.

I. Physics Justification

Photons produced in hadronic collisions at large transverse momenta can arise from several sources. Figure 1 displays the simplest (p_T^{-4}) mechanisms available in the framework of the QCD theory of strong interactions.[(1)] In Fig. 1(a), a quark from one of the hadrons collides with



(a) (b) (c) (d)

Fig. 1 Source of direct photons

a gluon from the second hadron, providing both a photon and a quark with large values of p_T (the unscattered accompanying quarks are rearranged by subsequent soft scatters). This kind of quark-gluon Compton scattering may provide the principal source of photons in p-nucleon collisions. Figure 1(b) illustrates another elementary source of photons, namely, that due to the annihilation of a quark with an antiquark to yield a photon and a gluon. This process is expected to be an important source for photons in meson-nucleon collisions (especially for π^- beams) at large p_T. Thus, ignoring, for the moment, other sources of direct photons, a photon trigger would signal the presence of an accompanying gluon or quark jet. In principle, therefore, by examining the associated hadrons, a direct photon provides one of the cleanest ways of studying the nature of the dressing of constituents.

Additional sources of direct photons are available in the quark Bremsstrahlung or constituent interchange diagrams (CIM) of Fig. 1 (c) and (d). Here a quark radiates following a high-p_T collision , or the incident meson is scattered by a quark, producing a photon at large p_T and a single quark. In most low-order graphs of the kind shown in Fig. 1 the photon is emitted on one side of the collision axis while the accompanying constituents appear on the away side. (This fact can be used to enhance contributions from QCD/CIM mechanisms at the trigger stage.)

Another source of photons is from the conversion of a virtual vector meson into a real γ (inverse of photoproduction). The least interesting photons are due to secondary background processes of the kind $\omega^o \rightarrow \pi^o\gamma, \eta^o \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^+\pi^-\gamma$, $\pi^o \rightarrow \gamma\,\gamma$. Although the inclusive production of mesons at large p_T is interesting in its own right, it is not central to the goal of our experiment, which is the observation and study of the direct production of photons.

Recent work by Bialas and Bialas, and by Krzywicki et al[(2)] on the scattering of quarks and gluons in nuclear matter has stimulated us into investigating the production of direct photons using several nuclear targets, with the specific goal of examining the correlation between the p_T of the photon and the nature of the accompanying hadronic system. Because quarks and gluons produced with large p_T hadronize over distances of several fermi, these constituents can scatter on their way out of the nucleus. Gluons are expected to scatter more and to provide softer jets than quarks. Thus by varying the nuclear target we might learn about the interactions of quarks and gluons with nucleons. The multiple scattering of constituents could provide a substantial increase in the γ yield in nuclei relative to hydrogen at large p_T.

Numerous estimates of rates for the production of photons at large p_T have recently appeared in the literature, all leading to the prediction that the observed ratio of QCD-induced photons to pions should increase with increasing p_T[3]. For pp collisions at 200 GeV this ratio is expected to be typically ~ 0.01 at $p_T \simeq 3$ GeV/c, and to increase to order unity at $p_T \simeq 7$ GeV/c. (The data of Baltrusaitis et al for p-Be collisions[4] indicate substantially larger yields, which might be attributable to the multiple scattering of constituents in nuclear matter.)

In contrast to the strong p_T dependence of photons that originate from hard QCD sources, photons produced through mechanisms similar to those leading to vector meson production should yield a γ/π ratio of $\leq 1\%$ ($\approx\alpha$), independent of p_T. CIM contributions are expected to yield γ/π ratios smaller than those from the first-order QCD diagrams and to display a somewhat weaker increase of the γ/π ratio with increasing p_T.

Evidence for direct production of photons at high p_T was recently summarized at the Fermilab Symposium on Leptons and Photons.[4] All the reported work involved either p-p (at the ISR) or p-Be (at Fermilab) channels. We believe that it is important to measure the direct photon signal in meson-nucleon reactions, and, at the same time, confirm previous findings in proton-nucleon collisions. This should preferably be done in the same set up.

There is essentially no information available at this time on the correlation between accompanying hadrons and the direct photons. We plan to study this question as part of this first phase of our program.

We view our proposal as a request for an exploratory investigation. In particular, the information we will obtain concerning the accompanying hadrons will be used to design an optimum hadron detection system, and the size of the γ/π ratio will guide us in redesigning our photon detector for the envisioned Tevatron phase of this experiment.

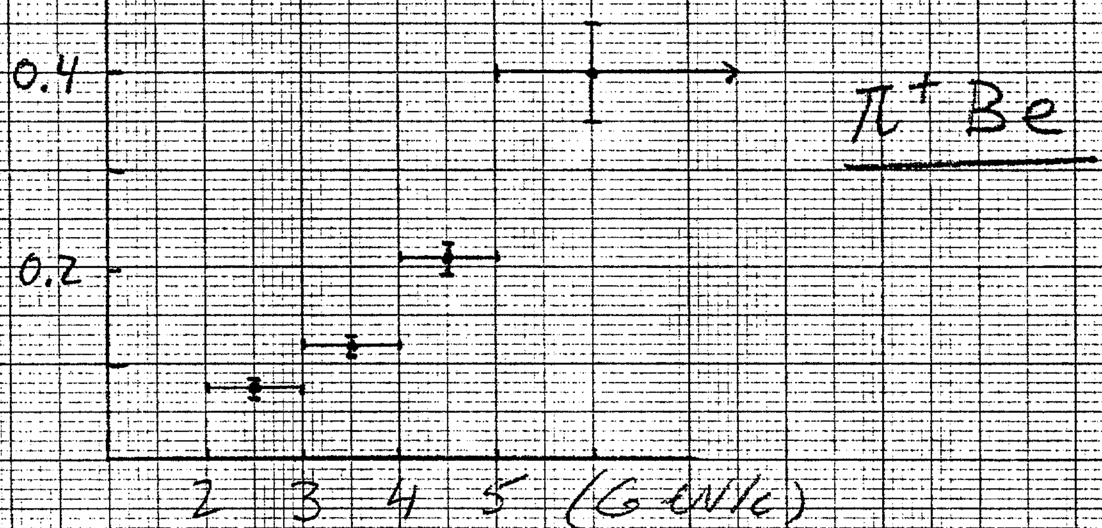
Table I indicates the yield of direct photons and π^o's that we anticipate at a beam momentum of 200 GeV/c. In calculating the π^o yield we used the inclusive $\pi^{\pm}p$ and pp data of G. Donaldson et al.[5] Extrapolations to higher p_T were based on an averaging of data from ISR and Fermilab.[6] For the photon yield we used data on the γ/π^o ratio whenever this was available. To estimate the QCD contribution to the prompt photon signal, we averaged several recent theoretical predictions. Finally, we assumed a 20% π^+/p fraction in the beam (this can be obtained without any selective filtration), 0.1 interaction lengths of Al and Be target material, 400 hours of beam at 3 x 10^7 particles/spill, and the geometry to be described in the following section.

Table I. Expected number of π^o and γ triggers for each target material.

p_T (GeV/c)	π^o		ALL SINGLE PHOTONS (≈ QCD PART)	
	pp	π^+p	pp	π^+p
2-3	1×10^7	2×10^6	4×10^5 (5×10^4)	1.5×10^5 (2×10^4)
3-4	3×10^5	8×10^4	1.5×10^4 (2000)	9000 (1000)
4-5	7×10^3	3×10^3	620 (250)	620 (150)
> 5	250	150	60 (30)	60 (30)

Figure 2 indicates how well we expect to measure the γ/π yield as a function of p_T for each target material. To obtain this graph we assumed that cross sections for η^o, and ω^o production are, respectively, half and equal to that for π^o. In the Monte Carlo we took account of resolution and backgrounds to the single photon yield from these sources (π^o,η^o and ω^o contribute the overwhelmingly largest backgrounds). For purpose of background subtraction we assumed that we can measure the π^o, η^o and ω^o cross sections to 10% accuracy and use such results to make subtractions to the observed photon

EXPECTED γ/π RATIOS



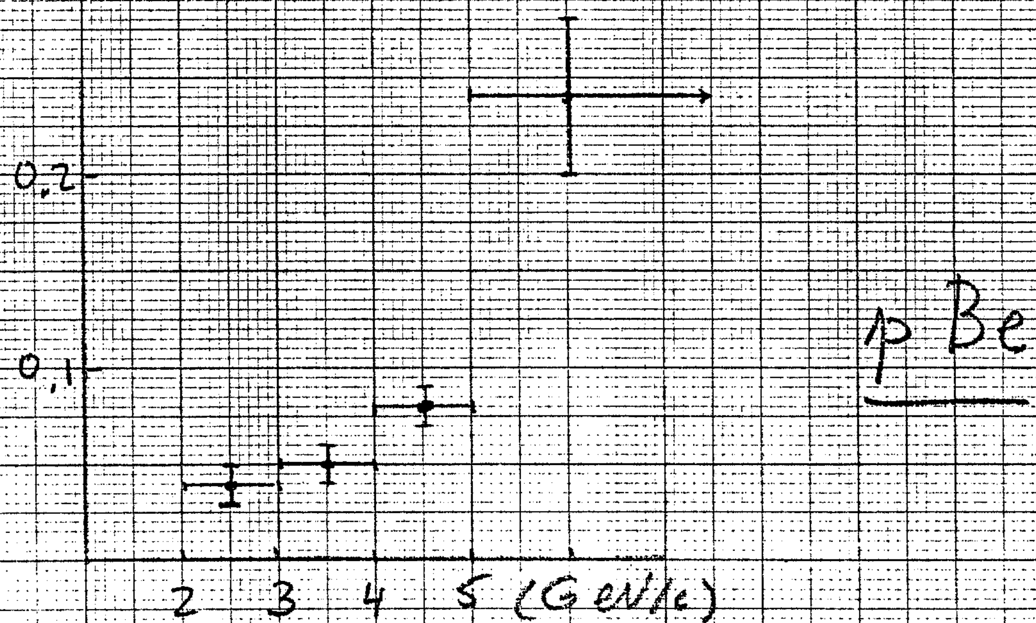


Fig. 2

yields. Because of the excellent position resolution and large acceptance of the LAC we expect our measurements of the γ/π ratio to be of better quality than those presently available. The new π^+ Be data and both the π^+ Al and p Al results, in addition to the correlations with hadrons, will be unique to this experiment.

If we include η^o, η', ω^o and other sources to the trigger, then for a p_T cut off of 2 GeV/c we would obtain ∿400 events per spill. Because reading such events into the computer effectively limits our data taking to ∿80 per second (at ∿50% dead time), we plan to set the threshold for the trigger between 2.5 GeV/c and 3 GeV/c during most of the data taking. Data will be obtained simultaneously from beryllium and aluminum targets, and we will therefore have a direct measure of the A-dependence of the production. If the trigger is quiet enough, we should then also be able to increase the beam intensity and thereby improve the yield at larger p_T.

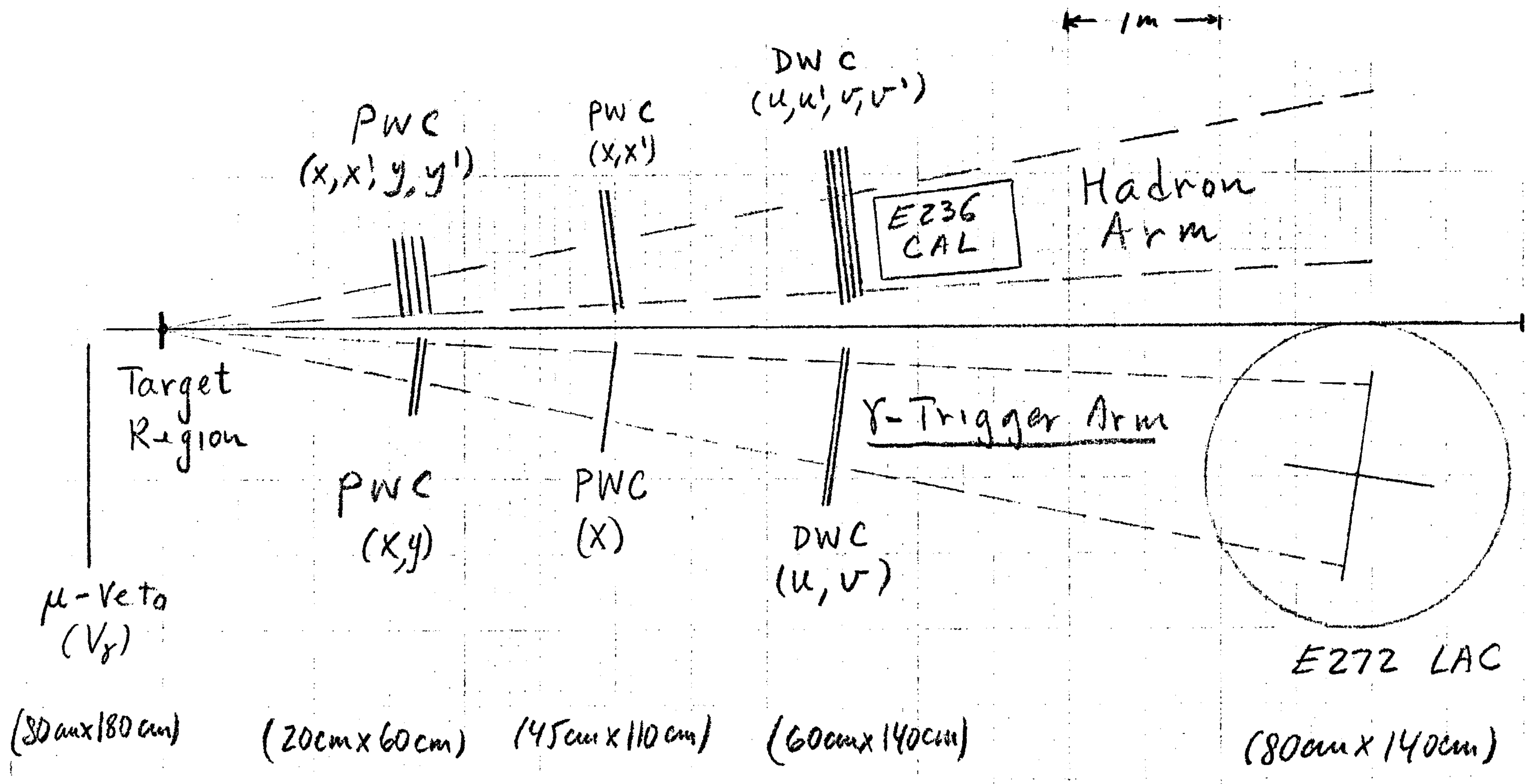
II. Experimental Arrangement

Most of the hardware for the experiment is presently located at the Meson Laboratory. The major items have all worked reliably for E272 or E236. Figure 3 shows a schematic diagram of the set up.

1. The Beam

The beam is the M-1 (west branch) line. We require $\geqslant 3 \times 10^7$ positive particles per spill at 200 GeV/c. The beam spot should be <5 mm horizontally and ∿1 cm vertically at about 1450 ft. from the Meson target. We require one threshold Cherenkov counter to distinguish pions from protons. The momentum bite is not at all critical, but the divergence at the target should be $\lesssim$1 mrad. All these conditions can be met quite readily using present beam elements.

We plan to stack lead and steel (or concrete) blocks on the east side of the M-1 line, well upstream of the target region, to reduce background sources of photons and neutrons in the liquid-argon calorimeter.



← 1m →
PWC
(x,x',y,y')
PWC
(x,x')
DWC
(u,u',v,v')
E236
CAL
Hadron
Arm
Target
Region
γ-Trigger Arm
PWC
(x,y)
PWC
(X)
DWC
(u,v)
μ-Veto
(Vγ)
E272 LAC
(80cm x 180cm)
(20cm x 60cm)
(145cm x 110cm)
(600cm x 140cm)
(800cm x 140cm)

Fig. 3

2. Spectrometer System

We propose to reposition our proportional and drift chambers on both sides of the beam to form a two-arm system straddling the beam. The eastern arm (electromagnetic trigger) will consist of three planes of proportional chambers (PWC) and one drift chamber doublet (DWC), followed by our liquid-argon calorimeter. The western (hadron) arm will be comprised of three PWC doublets (6 planes) and two DWC doublets. The entire system will have only a modest number of wires (<2500 PWC and <450 DWC). All components are available, and we only need to modify the support stands for the chambers.

As we indicated previously, the liquid-argon γ-detector will remain in the present position. Its steel pad will have to be extended westward by about 12".

The large veto wall that shields the γ-detector from interactions upstream of the target is also ready for installation. It consists of six 12" × 16" scintillation counters and a unistrut support structure.

The acceptance of both arms is of comparable size: 50 mr to 200 mr in laboratory angle (horizontal plane), and $\sim$0.7 radians in azimuth. This corresponds to an average (rapidity·azimuth) acceptance of $(\Delta y \cdot \Delta\phi/2\pi) \simeq 0.15$ per arm, centered approximately on 90° in the center of mass frame.

Figure 4 shows the acceptance of the experiment for γ, π^o, η^o and ω^o mesons, as function of p_T and x. For the calculation the detector was divided into a central region to be used for detecting single photons and a larger region for detecting π^o, η^o and ω^o. We required that all photons have energies in excess of 1 GeV to be identified as remnants of the primary mesons, and that the projected separation between photons exceed 2 cm in at least one projection.

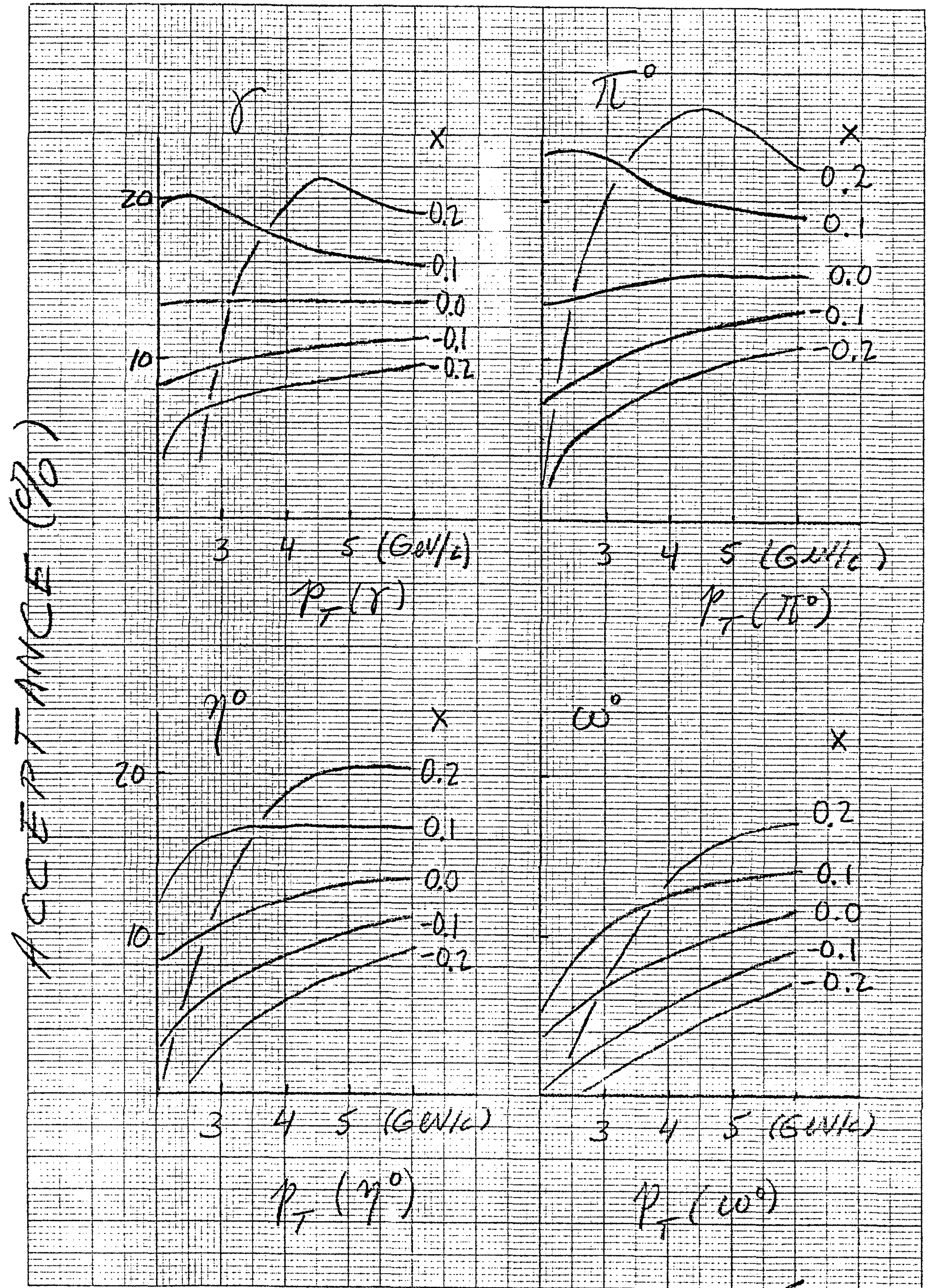

ACCEPTANCE (%)
γ
X
20
10
0.2
0.1
0.0
-0.1
-0.2
3 4 5 (GeV/c)
$p_T(\gamma)$
π°
X
0.2
0.1
0.0
-0.1
-0.2
3 4 5 (GeV/c)
$p_T(\pi^0)$
η°
X
20
10
0.2
0.1
0.0
-0.1
-0.2
3 4 5 (GeV/c)
$p_T(\eta^0)$
ω°
X
0.2
0.1
0.0
-0.1
-0.2
3 4 5 (GeV/c)
$p_T(\omega^0)$

Fig. 4

Note that we do not plan to use an analyzing magnet in this experiment. This is primarily because we feel that any advantages gained from having a magnet available would be more than offset by the additional problems of losing low-momentum e^+e^- pairs from conversions of π^o's in the thick targets. Without the magnet, electrons will not be deviated from the initial path of the γ and will therefore contribute to electromagnetic showers in the calorimeter.

3. Photon Detector

We expect to run the photon detector with pure liquid argon. Nevertheless, we have made a detailed study of the effect of CH_4 doping (using commercial grade methane) and feel that we can increase drift speeds by about a factor of three, without substantially affecting the quality of the signal, if this action becomes desireable. The present energy resolution of the electromagnetic calorimeter is approximately $\pm 15\%/\sqrt{E}$ and the spatial resolution is ± 0.8 mm. Two photons can be distinguished without difficulty if they are 2.5 cm apart. Thus we expect no problems with resolution or with π^o misidentification due to coalescence of two γ's for $p_T \lesssim 8$ GeV/c.

4. Target Assembly

We plan to employ a segmented target system of the kind indicated below.

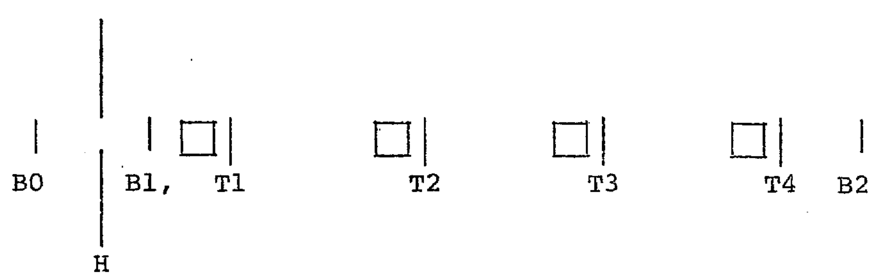


Fig. 5 Target Assembly

Four removable metal targets (Be and Al), each about $\frac{1}{20}$ of an interaction length ($\sim$2 cm) thick, will be spaced in 25 cm intervals. The T hodoscopes will be small $\frac{1}{8}$" thick scintillators that will be examined for pulse height to determine where the interaction occurred. The B-counter picket-fence hodoscopes, composed of several $\frac{1"}{8}$ wide, $\frac{1"}{2}$ high, and $\frac{1"}{8}$ thick (along the beam axis) scintillators, will be used for lining up the target assembly and for counting beam particles. These counters will also be examined for pulse height information. The H counter will be used to veto interactions caused by particles in the halo region of the beam. This target assembly is the only new item that has to be built from start for this experiment.

5. E236 Calorimeter

This is a 40" × 24" multipurpose calorimeter, segmented into 4" x and y strips.[7] There is a front electromagnetic section and a downstream hadronic part. This calorimeter will not affect the measurement of the γ/π ratio but will provide important information on the gross properties of the accompanying hadrons that would not otherwise be available. We are presently negotiating with Fermilab to acquire the use of this calorimeter.

III. Other Technical Details

1. Trigger

The trigger will consist of a beam-defining part and a high-p_T signal from the γ detector. In our preliminary test of last fall we determined that the γ-detector is quiet enough so that a p_T requirement of $\gtrsim$2 GeV/c should reduce the trigger level to below 10^{-5} of all interactions. (Because the absolute rates fall very rapidly with p_T, consequently, a small change in the p_T cut-off can have substantial effect on the trigger.)

The basic element of the p_T trigger will be a resistor chain that will weight deposited energy (in the front part of the γ detector) by the distance from the beam axis. The fast information from the LAC will be used in coincidence with the beam requirement. The trigger would consist of (see Figs.3,5):

$$p_T^{\gamma} \cdot B \cdot B0 \cdot B1 \cdot (T_1+T_2+T_3+T_4) \cdot \bar{H} \cdot \bar{V}_{\gamma}$$

where B is the coincidence of beam counters upstream of the target, V_{γ} is the veto wall and H is a halo counter. The T hodoscopes would be used to indicate that an interaction occurred in one of the targets.

2. Backgrounds

An estimate of background to the single-photon signal from decays of the kind $A \to B + \gamma$ can be obtained as follows. Assuming a parent spectrum of p_T^{-n}, it is straightforward to show that for isotropic decay the daughter/parent ratio at any p_T is independent of p_T and given by:

$$\gamma/A = \frac{1}{n}\left(1 - \frac{m_B^2}{m_A^2}\right)^{n-1}$$

For π^o production at 200 GeV/c, for example, the value of n for p_T>2 GeV/c is ∿12. Consequently, the background ratio of γ/π^o will be $\sim \frac{1}{6}$ at any p_T value (this is assuming that both photons from each π^o are counted!). In fact, from Monte Carlo studies, we expect that, for our detector configurations, $\lesssim$6% of the π^o's will yield two-photon topologies that could be mistaken for single-photon signals. Similarly, we expect the γ feed-through from $\eta^o \to \gamma\gamma$ to contribute ∿2% and the feed-through from $\omega^o \to \pi^o\gamma$ ∿0.6% to the γ/π^o ratio. Because we will measure π^o, η^o and ω^o production as a function of p_T, the correction for this background to the real γ/π^o yield should be straightforward. (The p_T distribution of the daughter γ's will tend to follow that of the parent.)

Hadronic backgrounds due to n, $\bar{n}$ and K_L^o interactions in the liquid argon calorimeter, simulating high-energy photons, are estimated to occur at levels of $\sim 10^{-2}$. If the (neutral hadron)/π^o ratio is $\sim \frac{1}{2}$ then this source should contribute ∿0.5% to the γ/π^o ratio.

Referring back to Table I, we see that if, as we believe, we can understand the corrections due to π^o and η^o background to $\sim$10% systematic uncertainty, then we can measure the γ/π^o yield to at least 20% accuracy for $p_T > 2$ GeV/c. Beyond 5 GeV/c the limitations should be statistical rather than systematic. (See Fig. 2.)

3. Summary and Scheduling

In summary, we wish to initiate a program for investigating the nature of processes that provide direct single photons. Our interest is to determine the cross section for production as a function of p_T, on nuclear targets, using both proton and pion projectiles. In addition, we wish to examine the nature of the accompanying hadron system. In this first phase of our experiment we will be able to determine γ yields for $p_T \gtrsim 2.0$ GeV/c, obtain the A-dependence, and a rough measure of the correlation between the photons and the accompanying hadrons. We will have information on electromagnetic and hadronic energy on the away side, the associated pseudorapidities and multiplicities for same-side and away-side jets. In addition, we will measure the π^o, η^o, ω and η' yield, and the spin alignment of the ω.

The results of this first experiment will be used to redesign the equipment and to prepare for a more complete attack on the problem. In particular, the appropriate size and cell width of the γ-detector, the nature of the anticipated hadron calorimeter and the kind of beam characteristics needed for at least an order of magnitude improvement in yields at large p_T will be gauged from the results of the first effort.

We can have all equipment ready by late spring or early summer. We hope to be scheduled for data taking during the fall running period, pending the approval of this proposal. (We can set up the experiment and perform preliminary tests while the M-1 Beam is being used by other experiments downstream of our equipment.) Within four months of the initial run we should have sufficient information to complete the design of the Tevatron experiment and submit a new proposal at that time. The continuation of this program at Tevatron energies, with an improved duty cycle and higher energies, will help substantially in our goal of examining γ production at the largest possible values of transverse momentum.

We wish to thank A. Bialas, J. D. Bjorken, A. Contogouris, A. Krzywicki and P. Landshoff for helpful discussions and correspondence.

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